Assessing the Applicability of Borehole GPR Surveying to Monitor Carbon Plumes in Storage Reservoirs at an Operating Power Plant

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ABSTRACT

The purpose of this research was to test the applicability of borehole radar methods to successfully monitor carbon plumes in deep saline aquifer formations post sequester and storage of CO_2. To perform this test, various software programs were used to allow for the most accurate and realistic feedback possible. Many variables and geophysical properties needed to be obtained including magnetic permeability, conductivity, and permittivity values for each subsurface layer modeled, as well as formation thicknesses, saturation levels, porosity values, and permeability values that affect the electromagnetic properties of the units in question. The combination of these geophysical and intrinsic physical properties is accompanied by electrical properties of the brine fluid/supercritical CO_2 solution.

The raw data for this investigation was obtained from previous testing by AEP and Batelle for the Mountaineer Power Plant, New Haven, West Virginia which is the site of an ongoing carbon sequestration project. The models represent one and two layer subsurfaces with interbedded shale and limestone caprocks, a sandstone or dolomite saline aquifer, and hypothetical carbon plumes. The models were created to determine the effectiveness, and permitting, the extent to which borehole ground penetrating radar can be utilized to monitor carbon storage and flow.

Acknowledgements

I would like to thank all of the people who helped make this research project possible, specifically my advisor Dr. Jeff Daniels, his associate Dr. Yuchan Yi, and Kyle Shalek for all of their guidance and assistance.

I would also like to thank Dr. Anne Carey who has always been more than willing to help me with any of my academic needs. And finally, I want to thank my family, especially my parents, for their constant support.

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Introduction

Objectives

This study has been conducted to determine the effectiveness of using borehole electromagnetic surveying to monitor carbon plumes in saline aquifers for carbon sequestration operations. Seismic cross-hole surveys have already been successfully used to monitor carbon plumes at several different carbon sequestration sites throughout the world, but the use of cross-hole electromagnetics, specifically ground penetrating radar (GPR), has yet to be thoroughly experimented with. My hypothesis is that by assigning realistic values to the model using an IDL program designed to create accurate GPR response models, that I will be able to detect the presence of the CO_2/brine plumes in the subsurface, as well as receive fairly accurate distance estimates for short range surveys, using geophysical data interpretation software. My concerns are that since GPR is typically used to image the shallow subsurface, that transmit and receive antennas will have to be placed in fairly close proximity to the plume itself.

Complications in determining the physical properties of the carbon plume arise from the fact that it is a mixture of supercritical CO_2 and preexisting brine solution from the injected saline aquifer. The differences in viscosity and density of the two fluids means that flow properties are entirely dependent upon the specific amounts of each solution, and each solution's density and viscosity. The goal of this project however was not to simulate a predictable flow pattern of the supercritical CO_2 brine solution, but rather test the ability of borehole electromagnetic techniques to successfully locate, within the aquifer layer of the model, an arbitrary target with similar physical properties and obtain an acceptable visual response from the interpretation software. Since this project was based simply on detection, logical values for the permeability, conductivity, and dielectric constant were assigned to the hypothetical carbon plume. This detail should be noted as an actual plume may have quite different properties as a result of the two fluids constant interaction with each other and the constantly increasing volume of CO_2 that would be pumping into the reservoir.

Global Warming: Carbon Sequestration Driving Force

Carbon sequestration efforts are a response to concerns about global warming. Globally, the consumption of fossil fuels is at an all time high. As a result, CO_2 emissions are also at an all time high accounting for 80% by weight of greenhouse gas discharge, and as can be seen in Figure 1, are exponentially increasing.

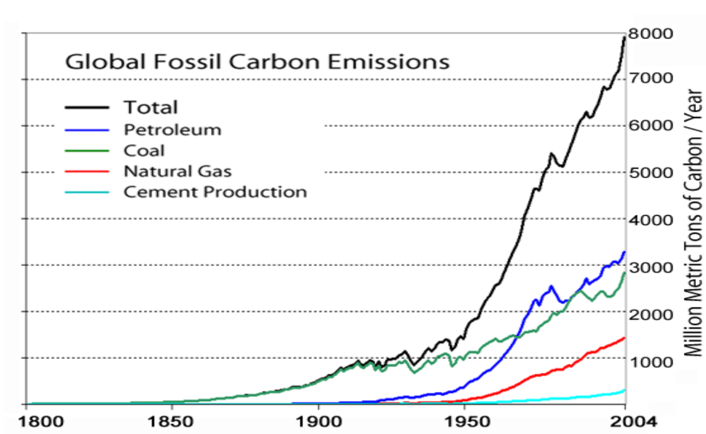


Figure 1
(http://mattrhodes.net/wordpress/?p=326)

The relationship between global warming and natural resource consumption has been a topic of debate politically, but the fact of the matter is that Earth's temperature and that of its atmosphere is slowly increasing, and studies have shown evidence of a correlation between the temperature rise and CO_2 concentrations in the atmosphere. Alternative energy sources are improving, but we as a society are not willing to abruptly change the way we live our lives and consume energy. Thus, carbon sequestration, a method for trapping CO_2 and transforming it into a supercritical fluid that can be pumped into the earth and stored, is gaining popularity and considered by many to be a necessary course of action to stabilize CO_2 emissions and global warming.

Background

AEP's 1,300 mega-watt Mountaineer power plant in New Haven, West Virginia is the site of an ongoing carbon sequestration project being conducted by AEP and Batelle. This location, as well as many other locations in the Ohio River Valley, is a coal burning power plant that consumes over 3.5 million tons of coal per year, which, along with its significant geological setting, made it an ideal candidate to be the first coal fired power plant in the U.S. to successfully implement both carbon capture and storage technology.

In general, there are three viable target areas for the storage of CO_2. Oil and gas reservoirs are ideal for carbon storage because of their sufficient porosity and permeability, presence of sealing layers, and the opportunity for enhanced oil recovery by migration of previously unobtainable hydrocarbons. Coal seams are also a desirable carbon storage location because of their confinement, the possibility for the acquisition of usable methane, and because they are often located in close proximity to coal burning power plants. The third option, and the option being utilized at the Mountaineer site, is deep saline aquifers. This alternative is advantageous because of the ability of saline formations to store large amounts of carbon, as well as their abundance throughout the United States. Using saline formations for CO_2 storage also presents many risks as hydraulic fracturing and geochemical reactions can lead to the degradation of confining layers and possible leaking, contaminating viable ground water or destroying ecosystems near the surface. (DOE, 2010)

Thus far, the Mountaineer plant has been successful as a result of a two phase plan. Phase one took place over the past five years and was funded by the U.S. Department of Energy (DOE), Batelle, AEP, and Alstom. It was completed in 2009 with the constant successful capture and storage of 1.5% of the plants carbon emissions, approximately .1 megatons of CO_2 per year. Preliminary operations for phase two has recently begun, and with a $334 million grant from DOE, the plant hopes to successfully capture and store 90% of its emissions from a 235 megawatt section of the plant, or 1.5 megatons of CO_2 per year by 2015.

The unique carbon capture procedure implemented at Mountaineer was developed by Alstom and has been termed the ‘chilled ammonia’ process. The process literally chills the flue gas and uses ammonium carbonate to absorb CO_2. This results in ammonium bicarbonate which is then reheated and converted back to ammonium carbonate which is used to repeat the entire procedure. (AEP: Carbon Capture and Storage)

Geologic Setting of Site

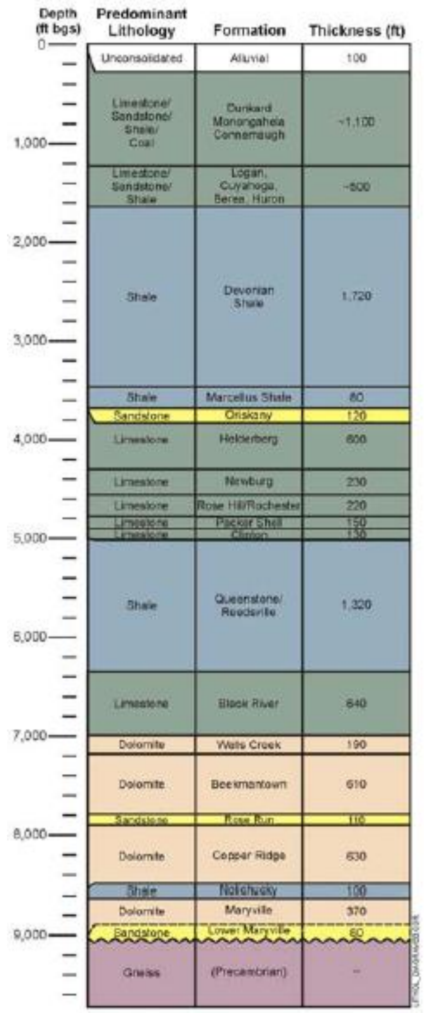
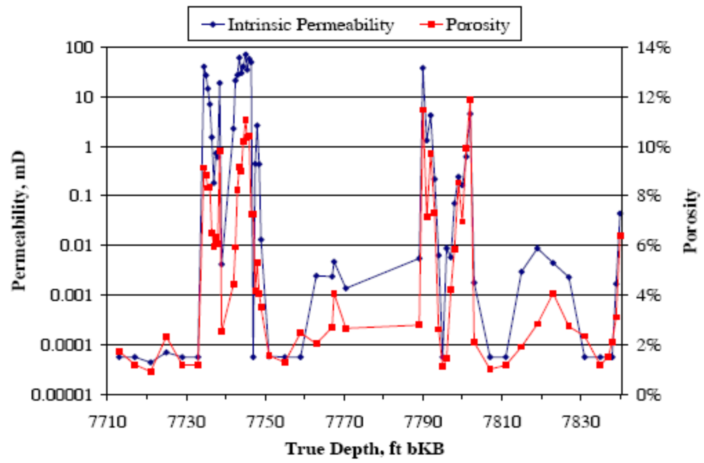


Figure 2
(Gupta, Final Technical Report)

The AEP Mountaineer Power Plant in West Virginia is located in the southern portion of the Ohio River Valley. This area is part of the Appalachian Basin and contains units dipping eastwardly and slightly to the south. As can be seen in figure 2, obtained from Batelle's Final Technical Report by the use of drill core samples, the units in question consist primarily of interbedded limestones and shales the first 7,000 meters. These units date back to the middle and upper Ordovician, approximately 470 to 444 million years old, and continue stratigraphically upwards through the lower and upper Silurian, approximately 444 to 416 million years old, the lower, middle, and upper Devonian, approximately 416 to 359 million years old, the lower and upper Mississippian, approximately 359 to 318 million years old, the lower, middle, and upper Pennsylvanian, approximately 318 to 299 million years old, and into the lower Permian, approximately 299 to 284 million years old. The sequence is topped off by roughly 100-200 feet of much more recent, a few thousand years old, unconsolidated alluvial deposits. These 7,000 feet thick sequences of shales and limestones are ideal caprocks for the interbedded sandstones and dolomites that lie beneath.



Porosity and Permeability from Wireline Log and Core Samples of the Rose Run Formation

Figure 3

(Gupta, Final Technical Report)

These sandstone and dolomite layers, specifically the Rose Run Sandstone and Copper Ridge Dolomite, are of substantial thickness and have sufficient porosity and permeability values to serve as CO_2 reservoirs. Well logs, illustrated on the next page in figure x, and the before mentioned core data have provided much information about these two possible injection formations, providing porosity values of 10-50% and average permeability values of approximately 4-8 mD, but up to 40 mD for the Rose Run Sandstone, and over 15% and 50 to several thousand mD respectively for regions of the Copper Ridge Dolomite. Well log interpretation is based on Archie's law which relates the fluid saturated rock resistivity (R_t), the lithology coefficient (a), porosity (ϕ^m), the brine saturation (S^n_w), and the brine resistivity (R_w) with the following relationship:

1.) $$R_t = \frac{a}{\phi^m}\frac{R_w}{S_w^n}$$

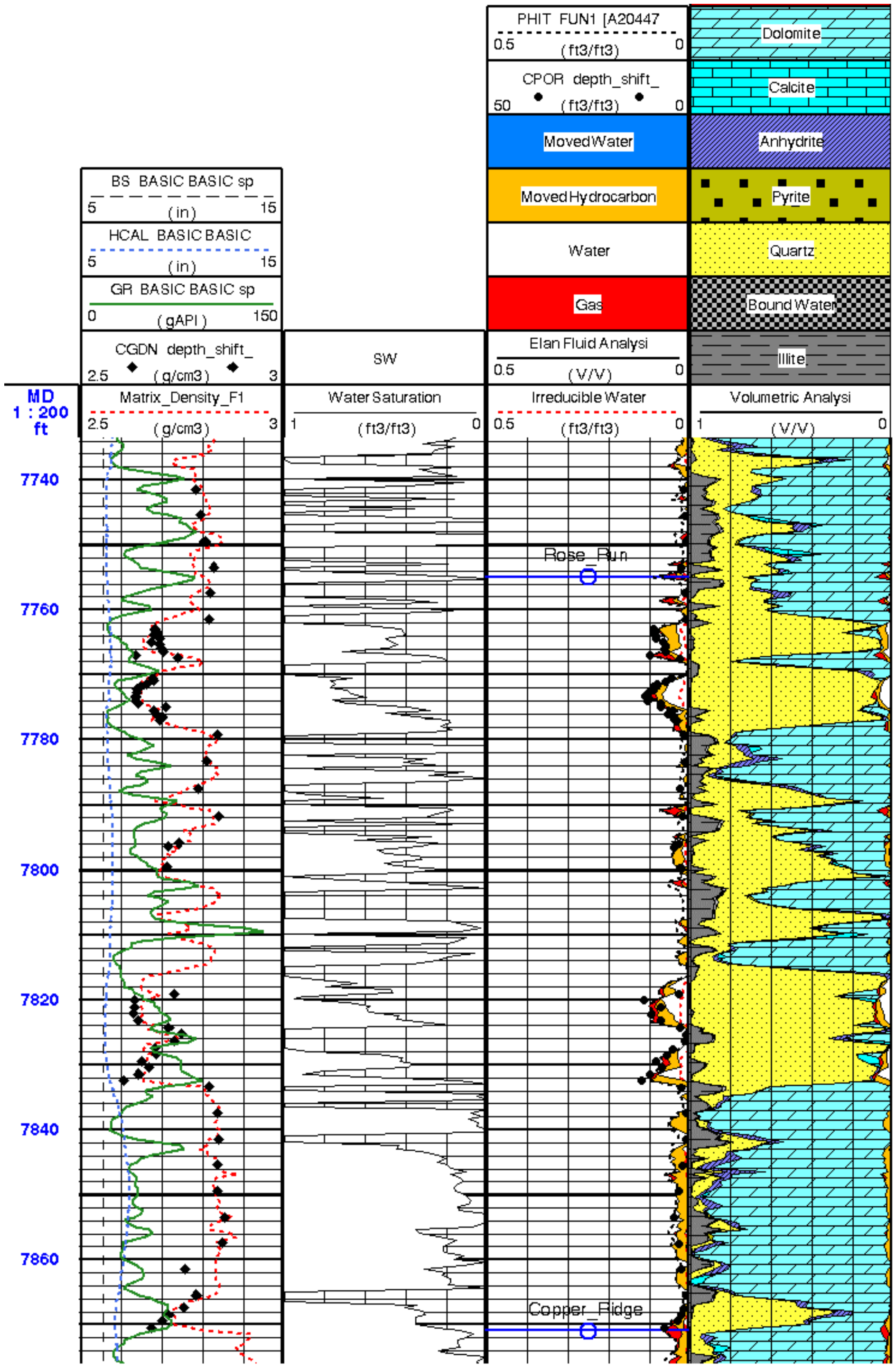


Figure 4

(ELAN Study)

Geophysics for Subsurface CO_2 Monitoring

Geophysical surveying uses a variety of geophysical principles to obtain an image of the subsurface. There are many different types, for example seismic, electromagnetic, radar, electrical, and gravity, but they all use basic physical laws that govern the reactions of materials to get an image of the subsurface without the use of invasive techniques. Geophysics is an obvious candidate to monitor carbon plumes, and is the only possible way to monitor CO_2 without actually drilling a hole in the ground and using sensing devices to detect the flow.

Ground Penetrating Radar for Subsurface Analysis of CO_2

Ground penetrating radar, or GPR, is a time-dependent geophysical survey technique that utilizes electromagnetism and is frequently used for locating objects or geological inhomogeneities in the near subsurface. It can be used to produce 2D, 3D, and 4D (color) plots. GPR can be used on the surface or in boreholes, allowing this research to test its applicability in monitoring carbon plumes. The physics that allows GPR and other forms of electromagnetic induction geophysical techniques starts with a transmit coil that produces low frequency electromagnetic signals. These signals create what is called the primary electromagnetic field. This field induces eddy currents, or an induced field, in objects in the subsurface, which consequently create a secondary electromagnetic field. The primary and secondary fields are summed into a vector field which is then measured by a receive coil to determine any magnetic anomalies in the subsurface.

The velocity with which the electromagnetic wave travels through a material is directly related to the dielectric constant (k) and the permittivity (ε) of the material, as well as its conductivity and magnetic permeability. Permittivity, by definition, is the ability of a material to be polarized by an electric field. The dielectric constant is also known as the relative permittivity, and is the ratio of a material's permittivity to the permittivity of a vacuum (ε_o), resulting in the relationship $k = \varepsilon/\varepsilon_o$. Velocity changes represent changes in material composition; the greater the change, the higher the amplitude of the reflected wave. When waves encounter a new material, some of them are reflected back to receiver antennae, and some are refracted further into the subsurface. Thus, by emitting many waves at different locations, a fairly clear image of the subsurface can be created. The relationship between the angle of incidence and the angle of refraction can be expressed by Snell's Law which states:

2.) $$\frac{v_1}{v_2} = \frac{\sin \phi_1}{\sin \phi_2}$$

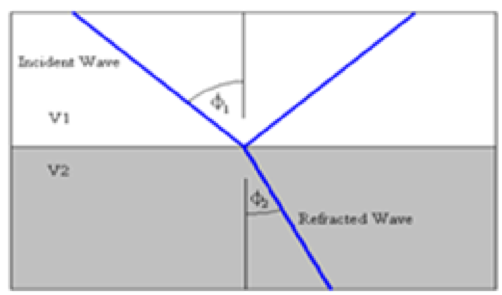


Figure 5

Here, v is the velocity of each corresponding layer, and ϕ is the angle of the incident wave or the angle of the refracted wave. Snell's Law is also the basic principle behind seismic reflection surveying. It can be rewritten to illustrate the before mentioned relationship between velocity and the dielectric constant as

3.) $$\frac{\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}} = \frac{v_1}{v_2} = \sin\phi_1$$

METHODS

Geophysical Modeling

Modeling is a process frequently used for electromagnetic and seismic geophysical applications. There are two basic types: forward modeling, which is generally referred to as modeling, and inverse modeling, referred to as inversion. Modeling, in the forward or direct sense, uses data and knowledge obtained from a specific site, such as seismic responses and well logs, to create synthetic data such as the predicted response of electromagnetic or acoustic waves traveling through the subsurface mediums. Inversion in contrast is the reverse process, generating a log or model of the subsurface from known stratigraphic information and seismic data. To summarize, modeling creates data from a model, and inversion predicts models from data. Since the data in this experiment is the acoustic wave response, it is considered forward modeling.

Software

Linux

This study required the use of a Linux interface for Microsoft Windows, X-Win32, to access the necessary programs and files held on the vlowk cluster account operating from the Ohio State Physics Research Building. Linux is a Unix-like operating system, which allows users to operate their systems directly through command like interface (CLI), or through a graphical user interface (GUI).

The main difference between a Linux operating system and Microsoft Windows' operating system is the way in which the user communicates with the system's kernel. With Linux the user must use a code language that the system recognizes to execute different tasks and launch programs. Windows, as most know, provides the user with 'point and click' accessibility which is much more simple to use, but lacks the ability to access and exchange information and programs safely over a server. Linux permits users access to all files and programs held on the particular server that they are connected to, allowing for quick and easy access to a vast collection of data stored on the Linux based mainframe.

Figure 6

(X-Win32 left, SSH right)

Linux has gained popularity commercially in recent years because of its versatility and its modularity. It has the ability to discard software layers, such as Microsoft's desktop windows and menus that are not necessary and keep only those that are. Linux also offers programmers a much more vast collection of editors and compilers to create new programs targeted at specific tasks. If the user still wants some of the simplicity of Windows, Secure Shell (SSH) can be used in combination with Linux, providing the user with a Windows-like operating platform that communicates directly with the Linux server for easy file modifications, as well as many other applications.

IDL and GUI

The programming platform used to create the modeling software used in this experiment is IDL, or interactive data language, and it operates with the GUI, or graphical user interface.. IDL is a device used to make visual representations of raw data to learn more about it. It is functional with all of the most popular operating systems. A GUI is a 'point-and-click' way of communicating with the kernel without having to type out command lines.

PFDTD

PFDTD stands for perfectly matched layer, P, finite difference time domain. Basically, it performs calculations for the electric and magnetic fields and outputs results for visualization. Its computational domain is the Maxwell region because it operates on the principles of Maxwell's equations. This particular FDTD simulation software was designed by members from the Ohio State University School of Earth Sciences and Department of Electrical and Computer Engineering. It is capable of handling very complex, realistic subsurface models.

GPHYZ

Gphyz is a software program written in IDL language by my advisor, Dr. Jeffrey J. Daniels, created to analyze Ground Penetrating Radar (GPR) data. Gphyz is a GPR 2D/3D/4D (color) display and interpretation package that accepts inputs from sensors and software models with the use of IDL. It is able to handle such operations as linear frequency filtering, amplitude discrimination filtering, batch data processing, and decimation and interpretation of lines and traces.

PROCEDURES

The IDL interface used in this experiment required the input of property values for all materials to be modeled in the subsurface. First, a block model of the subsurface which includes all necessary variables to perform a GPR survey is created. The program necessitates assigning specific dimensions for the block size, including cell size dh in meters, and the max grid dimensions for the X, Y, and Z directions in meters. Electromagnetic properties of the background are also required. These properties consist of the highest dielectric constant, the relative magnetic permeability, the conductivity in SI, the number of permittivities, conductivities, and permeabilities, the number of antenna frequency ranges, the low and high frequencies in Megahertz, and the delay factor of the source excitation pulse. In addition, the exact transmitter and receiver locations must be specified by clarifying the center locations of the X, Y, and Z coordinates for the receiver and the antenna, and the number of traces and the distance between them for the X dimension, the number of lines and the distance between them for the Y direction, and the number of horizontal planes and the distance between them for the Z direction. The X, Y, Z origin for this initial block configuration has (0,0,0) oriented in the left, front, bottom corner of the block. This procedure is illustrated in Figure 7.

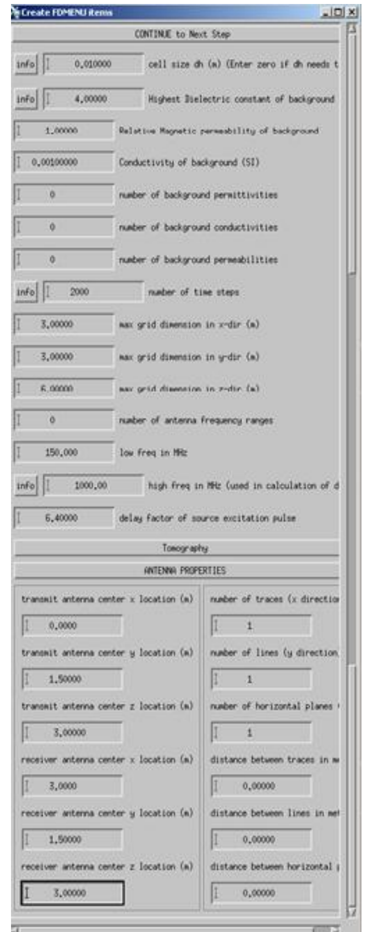


Figure 7

Once the initial block properties have been attributed, the 3D bodies in the subsurface must be constructed. This requires inputting the number of layers to be created, and the thickness of each layer. The model recognizes cells rather that meters, so each input in meters is automatically attributed a coinciding number of cells. Each layer is assigned electromagnetic property values for relative permeability, conductivity, and the dielectric constant. These values are also used to set a standard noise deviation that is frequently experienced in GPR surveys. Once all these values have been input, a subgrid size is selected allowing for the opportunity to make the subgrid up to eight times, and as small as one eighth the size of the original block grid before assigning it dimensions and magnetic properties.

If a 3D target is desired for the subsurface, a number of different shapes can be selected, and the exact location and magnetic properties are assigned. Once the subsurface and target are constructed (Figure 8), the results are stored in a format that is then converted to another format for batch processing using a specifically designed Linux program. These programs produce a subdirectory for each trace, line, or layer, which are then merged into one file using a specifically designed routine. These merged files are now capable of being uploaded into GPHYZ for geophysical processing, which displays the trace of the wave and shows an image the expected GPR response.

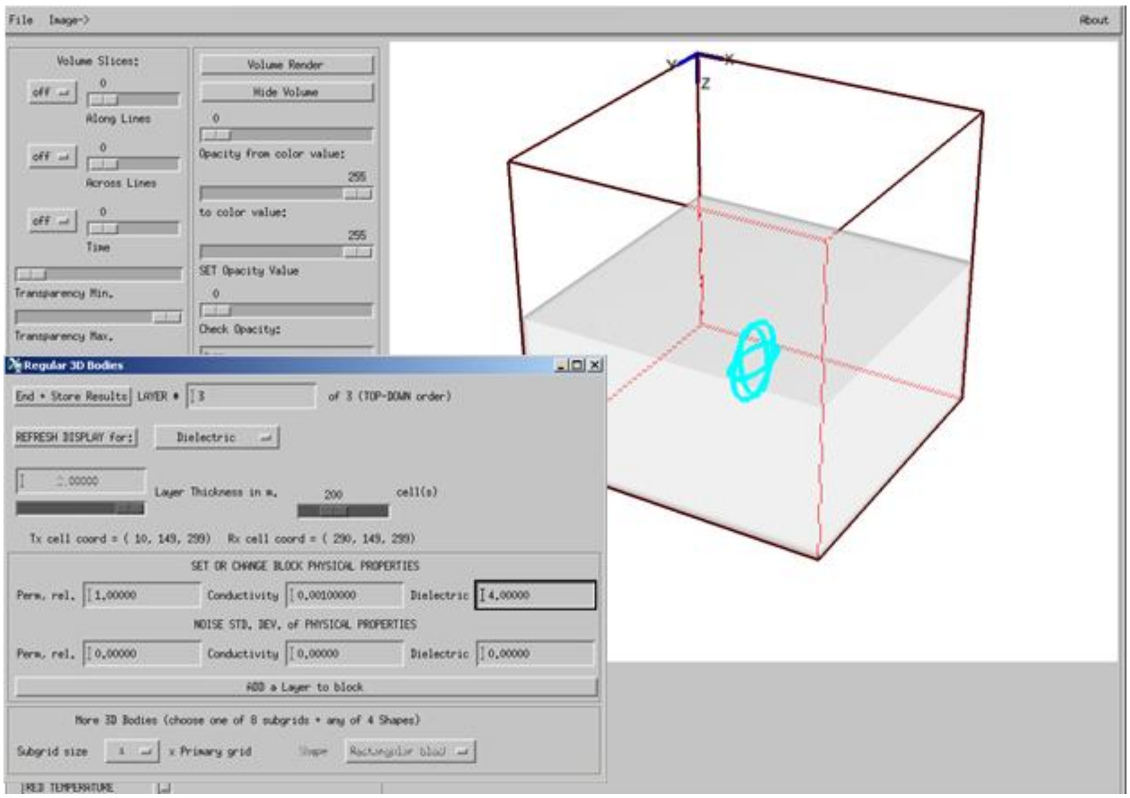


Figure 8

DISCUSSION

Results

The GPR models created in this experiment were able to successfully detect the presence of a carbon plume within a realistic generated subsurface environment. However, due to size and space limitations, a scaled down version of the subsurface scenario had to be created, which still leaves the question of the feasibility of using GPR to monitor carbon plumes from a substantial distance. The GPHYZ output obtained can be seen in the following, Figure 9.

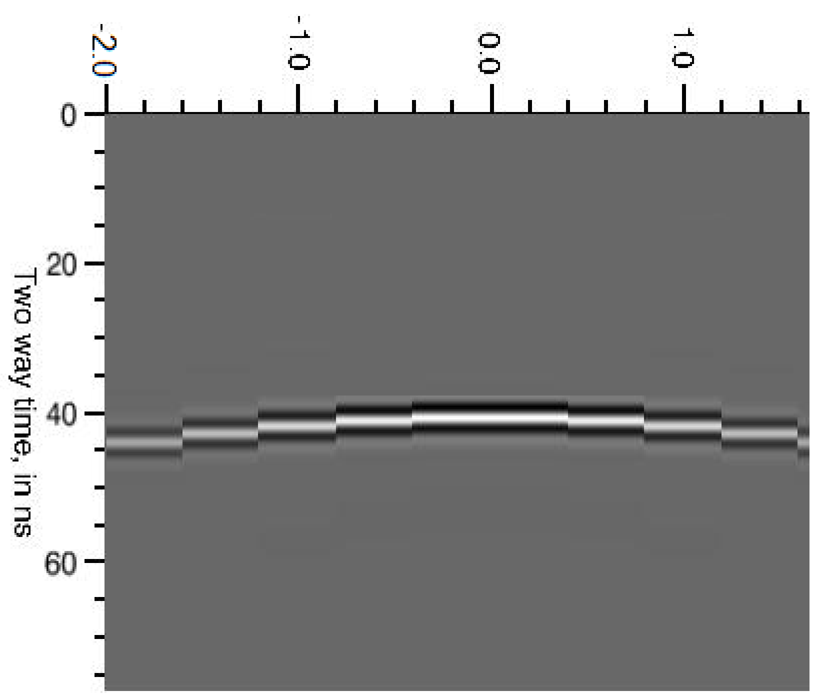


Figure 9

Future Research

This research was a success in providing the knowledge that GPR can be used to detect carbon plumes for CO_2 sequestration in deep saline aquifers. However, much more work needs to be done to test the extent to which the use of GPR is applicable in these situations. More complex 3D models representing larger volumes of subsurface need to created and tested, and CO_2 plume properties need to be further investigated. This research proves further investigation is a worthwhile project and could lead to the permanent use GPR for carbon storage monitoring.

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APPENDIX

Block Model Parameters

BLOCK EM PROPERTIES	
cell size DH (m)	0.01
highest dielectric constant of background	8
relative magnetic permeability of background	1
conductivity of background (SI)	0.001
number of background permittivities	0
number of background conductivities	0
number of background permeabilities	0
number of time steps	1000
max grid dimension in x-dir (m)	4
max grid dimension in y-dir (m)	4
max grid dimension in z-dir (m)	6
number of antenna frequency ranges	0
low freq in MHz	150
high freq in MHz	1000
delay factor of source excitation pulse	6.4

Layer & Target Properties	
thickness of aquifer layer (m)	2
relative magnetic permeability of aquifer layer	1
conductivity of aquifer layer	0.006
Dielectric constant of aquifer layer	8
thickness of caprock layer (m)	2
relative magnetic permeability of caprock Layer	1
conductivity of caprock layer	0.001
dielectric constant of caprock layer	6
relative magnetic permeability of plume	1
conductivity of plume	0.0001
dielectric constant of plume	15